Hillslope Soils and Organic Matter Dynamics within a Native American Agroecosystem on the Colorado Plateau

J. B. Norton,* J. A. Sandor, and C. S. White

ABSTRACT

Zuni farmers of western New Mexico demonstrate knowledge about soil and hydrological processes that link upland watersheds to alluvium-derived soils that have crucial cultural, ecological, and hydrological functions. To define how hillslopes contribute to productivity of soils derived from alluvium, we studied soil-vegetation-landform parameters in three headwater drainages on the Zuni Indian Reservation. Analyses along eight summit to toeslope transects show that soil properties follow parabolic and linear trends with changes driven by elevation, lithology, and vegetation in the mesa-canyon pinyon–juniper–Gambel oak (*Pinus edulis* Engelm.–*Juniperus* spp.–*Quercus gambelii* Nutt.) woodlands. Total organic C, N, and P concentrations in surface horizons follow negative parabolic trends and are highest on wooded backslopes and lowest on summits and toeslopes. Inorganic N and available P concentrations and total organic to inorganic N and P ratios increase linearly from summit to toeslope. Taken together, soil, landform, and vegetation data suggest: (i) summit positions are relatively stable with immobilizing microbial environments; (ii) inorganic nutrients increase progressively down steep and erodible backslopes as inputs of forest litter are mixed with surface soil; (iii) influx of mixed sediment and organic materials from backslopes maintains concentrations of inorganic nutrients on footslopes and toeslopes. Entrenchment of drainage ways can circumvent these translocation processes. Without the influx of organic materials, footslopes and toeslopes may become nutrient-depleted as immobilization becomes the dominant microbial process. The results underscore the importance of functional connectivity between upland hillslopes and alluvial soils.

Some of the oldest agricultural soils in North America lie within the Colorado Plateau on alluvial fans farmed by the Zuni of western New Mexico (Damp et al., 2002). Zuni farmers recognize the role of upland hillslopes in their strategy to produce corn (*Zea mays* L.) and other crops in the semiarid environment (Sandor et al., 2002). They actively seek fresh deposits of sediments and organic material for cultivation, and work to enhance fluvial processes that link hillslopes to their fields (Cushing, 1920; Norton et al., 2001; Norton et al., 2002). Sustained productivity of Zuni agricultural soils exemplifies the importance of hillslope processes that support crucial cultural, ecological, and hydrological functions of headwater alluvial fans (Bull, 1997; Peterson et al., 2001). This ancient agriculture, which is intimately linked to natural landscape processes, creates an excellent setting for investigating important relationships between upland hillslopes and nutrient cycling and retention in alluvium-derived soils of headwater ephemeral streams.

Peterson et al. (2001) create a convincing case for conservation that maintains or restores the storage capacity of headwater streams. Their data show that headwater streams play a key role in the physical and biological integrity of downstream waterways because of their great extent on the landscape and their proximity to uplands that are source areas for runoff, sediments, and nutrients. Properly functioning headwater systems retain and recycle a large portion of the nutrients, particularly N, from uplands. This retention and recycling creates the richest soils and highest biological productivity in many arid areas. Bull (1997) points out that many Native American farmers recognized the value of the system and their activities maintained these functions, while modern practices often have the opposite effect.

Although many authors describe hillslope models that link soil and nutrient-cycling processes from summits to alluvial toeslopes (Ruhe and Walker, 1968; Conacher and Dalrymple, 1977; Schimel et al., 1985; Aguilar and Heil, 1988), the unique terrain of the Colorado Plateau creates lithologically segmented hillslopes different from those described in accepted hillslope models. Our objective was to develop a hillslope model based on linked slope morphology, soils, vegetation, and nutrient dynamics on the Zuni Indian Reservation in New Mexico. We focused on hillslopes in headwater drainages whose sandy to loamy alluvial fans have been used by generations of Native American farmers. This type of farming continues to be an essential component of many Native Southwestern cultures. By storing runoff and sediments, mitigating destructive floods, and producing diverse, productive vegetation for livestock and wildlife, alluvium-derived soils of small upland watersheds also serve vital ecological and hydrological functions (Lagasse et al., 1990; Bull, 1997).

MATERIALS AND METHODS

We analyzed soil, landform, and vegetation distribution in three small watersheds above long-term runoff agricultural fields on the Zuni Indian Reservation, New Mexico. The reservation lies on the southeastern part of the Colorado Plateau at 1800 to 2400 m elevation (Fig. 1) and receives an average of 300 mm of precipitation annually, the majority of which often comes during thunderstorms in July, August, and September. Hillslope morphology on the Zuni Indian Reservation, as in much of the Colorado Plateau, is largely a function of horizontal layers of Cretaceous sandstones and shales. At our study sites, relatively indurate, cliff-forming sandstones act as caprocks over more erodible, slope-forming shales, shaping hillslope profiles much like that defined by Conacher and Dalrymple (1977) (Fig. 2). Headwater drainages typically form

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Published in Soil Sci. Soc. Am. J. 67:225–234 (2003).

Abbreviations: SOM, soil organic matter.

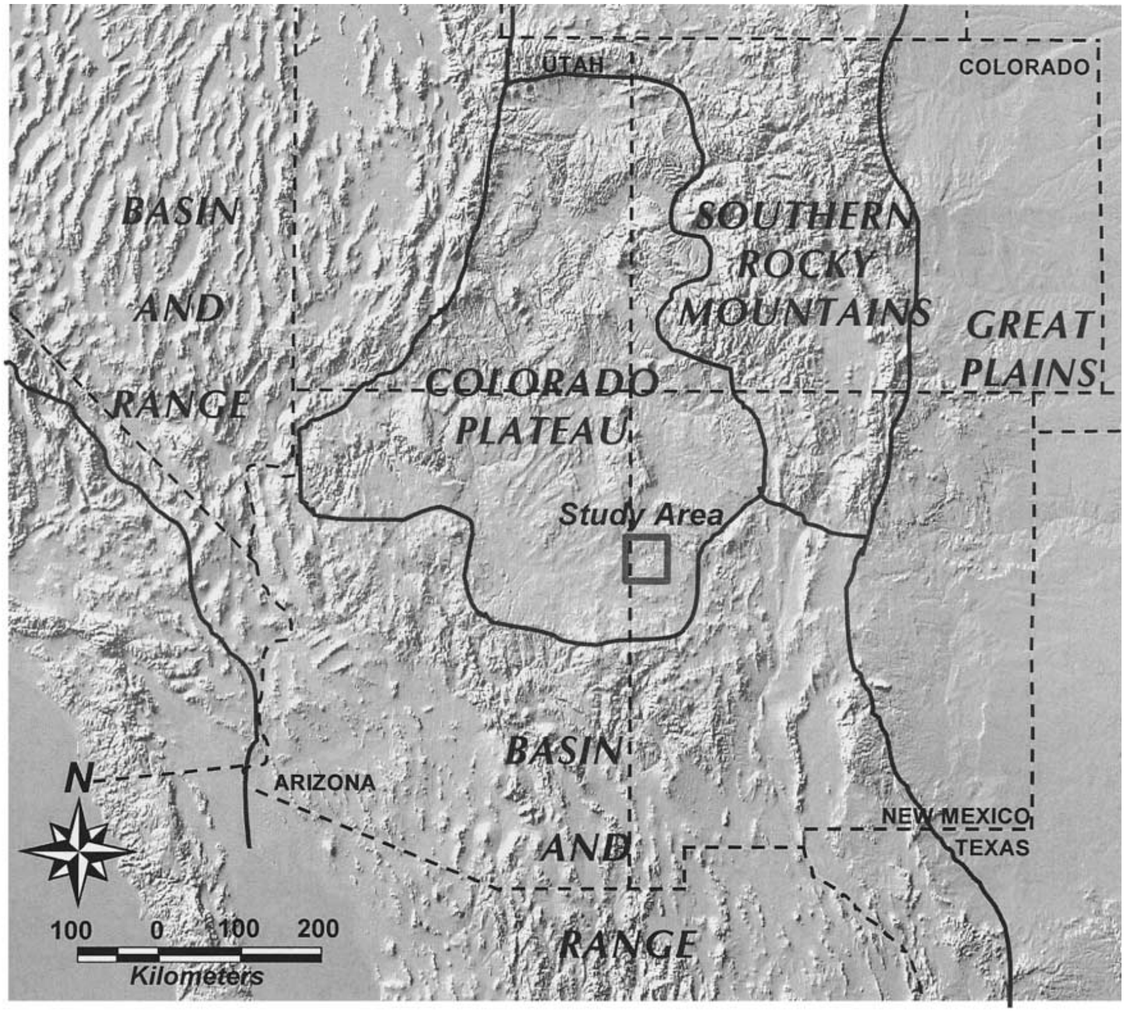

Fig. 1. Study area location and physiographic provinces of the Southwest (modified from Cordell, 1997).

narrow, steep-walled canyons that drain onto broad alluvial valleys.

Zuni is one of 19 pueblo tribes of Arizona and New Mexico well known for persistent, agriculturally based traditions (Ferguson and Hart, 1985). Zuni subsistence depended on corn grown in nonirrigated fields for at least 2000 yr (Kintigh, 1985; Damp et al., 2002). Socio-economic change and assimilation policies beginning with U.S. occupation of Zuni lands in the mid 19th century caused drastic declines in agriculture (Cleveland et al., 1995). We selected three study sites (the Sanchez, Laate, and Weekoty sites) that are representative of headwater drainages above long-term nonirrigated agricultural fields. We worked closely with a group of traditional Zuni farmers who assisted with study site location and provided invaluable insights about Zuni farming techniques.

The Sanchez watershed (68 ha) drains to the north with east- and west-facing hillslopes, the Laate watershed (7 ha) drains to the southwest with northwest- and south-facing hillslopes, and the Weekoty watershed (125 ha) drains to the east with north- and south-facing hillslopes (see Fig. 3). Steep-walled canyons cut into sandstone and shale members of the Gallup Sandstone formation characterize each of the watersheds (Anderson et al., 1989). The canyon-floor alluvium in each watershed is bisected by an entrenched ephemeral streambed (arroyo) ranging from a 1-m depth at the Laate site to >6 m at the Sanchez and Weekoty sites. In each case, the arroyo channel ends above a runoff agricultural field, near the canyon mouth.

To determine the aerial extent of each slope position, we mapped field observations in each watershed on fine-scale (1:5000; 50-cm contour interval) base maps (created by Koogle & Pouls Engineering, Inc., Albuquerque, NM, from 1988 aerial photography). Slope positions were entered as map units and area was calculated using Arc View 3.0 (Fig. 3).

We established two cross-watershed transects at the Sanchez watershed and one each at the Weekoty and Laate watersheds (Fig. 3) for a total of eight divide-to-drainage hillslope transects. To adequately sample the hillslopes, soil, vegetation, and landform samples were collected each 5 m along the transects at the Sanchez site. At the Weekoty and Laate sites, three samples were collected each 15 m along each transect: one on the transect and one 5 m each direction perpendicular from the transect. At each sample point we noted slope position and signs of erosion and deposition, classified and estimated soil cover, and collected 0- to 15-cm depth soil samples. Total vegetation cover by species, litter, bare soil, gravel, cobbles, stones, and boulders were estimated using a square frame constructed from PVC tubing. Plot size varied to reflect size of units sampled (Grieg-Smith, 1983), with 0.25 m^2 for herbaceous plants and other soil cover parameters, 1 m^2 for shrubs, and 4 m^2 for trees. We estimated cover classes in the field and then converted to percentages (cover class midpoints) and log

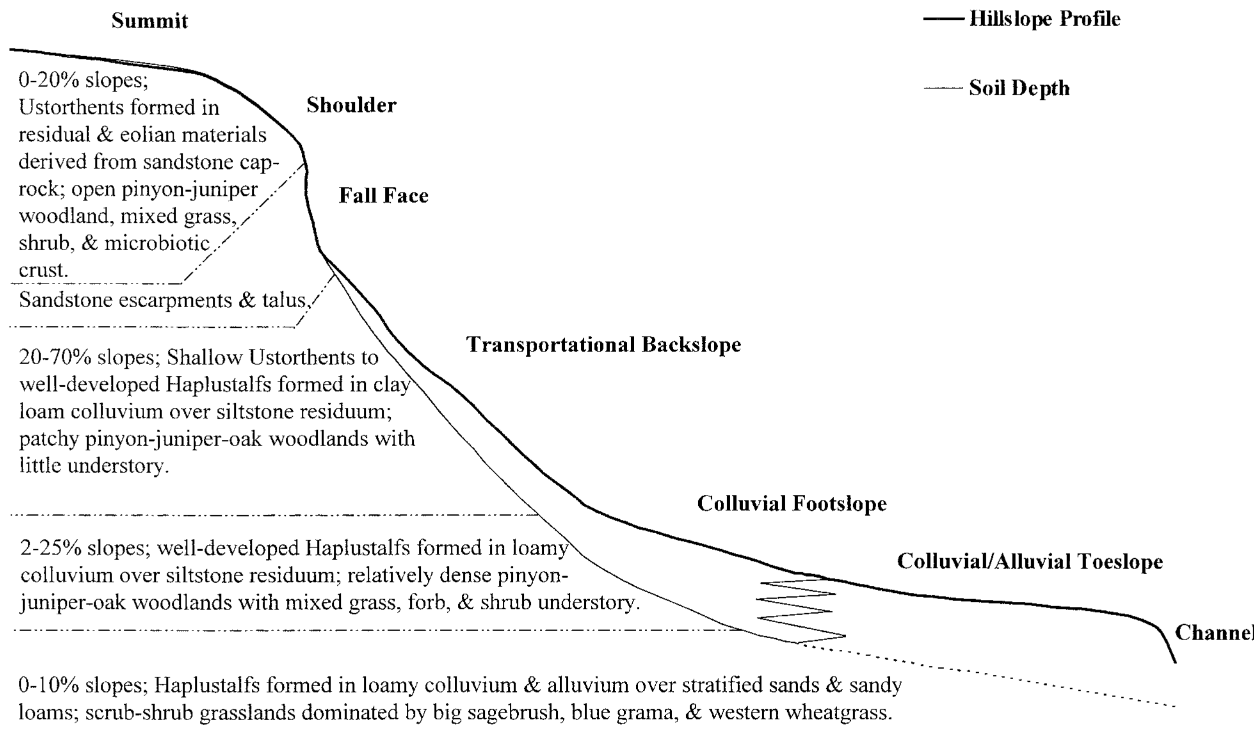

Fig. 2. Typical hillslope profile and distribution of soils and vegetation on eight study hillslopes. All soils are in the Aridic subgroup.

10 transformed for analysis (Daubenmire, 1968). Soil samples consisted of five to seven 0- to 15-cm depth samples from within each 1-m^2 plot mixed and subsampled to provide one sample per plot. We described and sampled soil profiles in each slope position.

Soil samples were air dried in the field and transported to labs for chemical and physical analyses. Particle-size distribution was determined using the sieve and pipette method (Gee and Bauder, 1986), with samples pretreated with 30% hydrogen peroxide for soil organic matter (SOM) digestion and a sodium hexametaphosphate solution for clay dispersion. Soil pH was measured electrometrically using a 1:1 suspension (weight basis) of soil in distilled water using a glass electrode (McLean, 1982). Total C and N concentrations were determined on subsamples ground to pass a 76-μm sieve using a Fissions EA1100 dry combustion CNSHO analyzer (Fissions Inst., Inc., Milan, Italy). Inorganic C concentration was determined with a coulombmeter on a subset of samples and found to be insignificant relative to total C concentration in these surface soils. Total C values were therefore interpreted as organic C. Phosphorus was analyzed in soil samples from the Weekoty and Laate hillslopes and one of the Sanchez hillslopes. Total P concentrations were determined by alkaline oxidation (Dick and Tabatabai, 1977). Available P concentrations were measured by the Olsen extraction method (Olsen and Sommers, 1982). Nitrate (NO_3^-–N) and ammonium (NH_4^+–N) concentrations for the four Sanchez hillslopes were determined in 2*M* potassium chloride extracts with a Lachat flow-injection procedure (Method 12-107-04-1-B, Lachat Instruments, Milwaukee, WI).

Slope, soil, and landform observations were analyzed as a summit to toeslope continuum and as slope positions as defined by Ruhe and Walker (1968). For continuum analyses, we pooled data from all eight hillslopes based on relative distance from interfluve (actual distance/total transect length). We grouped points by increments of 10 relative distance units and calculated means and standard errors for those groupings. We then ran regression analyses (trendline function in Microsoft Excel) on means calculated for each 10-unit increment along the composite hillslope. We also ran regressions on data from each hillslope, the entire pooled data set, and on unweighted slope position means. The 10-unit increment analyses are presented here for SOM components because they represent transport and transformation along a continuum through the hillslope system.

For analysis of parameters that reflect slope position rather than a hillslope continuum (e.g., soil texture, SOM content, and vegetation), we calculated means and standard errors by slope position for the pooled data set. Means of slope position data from each individual hillslope confirm the pooled means. The means were compared by calculating least significant differences with the GLM procedure (SAS Institute, 1999). To ensure normal distribution and equivalent variance, particle-size distribution data (presented as percentages) were arcsine transformed and soil cover data (also presented as percentages) were log 10 transformed before statistical analyses. Additional information is available in Norton (2000, p. 180).

RESULTS

Distribution of soils on the eight hillslopes corresponds to distribution of the lithologically controlled slope positions in the steep-walled, mesa/canyon topography (Fig. 2, 3; Table 1). Summit positions in our study areas are generally broad, nearly level mesa tops with shallow Entisols formed in sandstone residuum or sandy eolian materials. Shoulder positions are often dominated by bare sandstone with pockets of shallow, sandy material. Backslope soils typically have A horizons formed in loamy colluvium over siltstone residuum with well developed argillic horizons on north and east facing slopes and none on south and west facing slopes (Table 1). This sequence—sandy or loamy surface materials over clayey subsoils—follows a continuum from

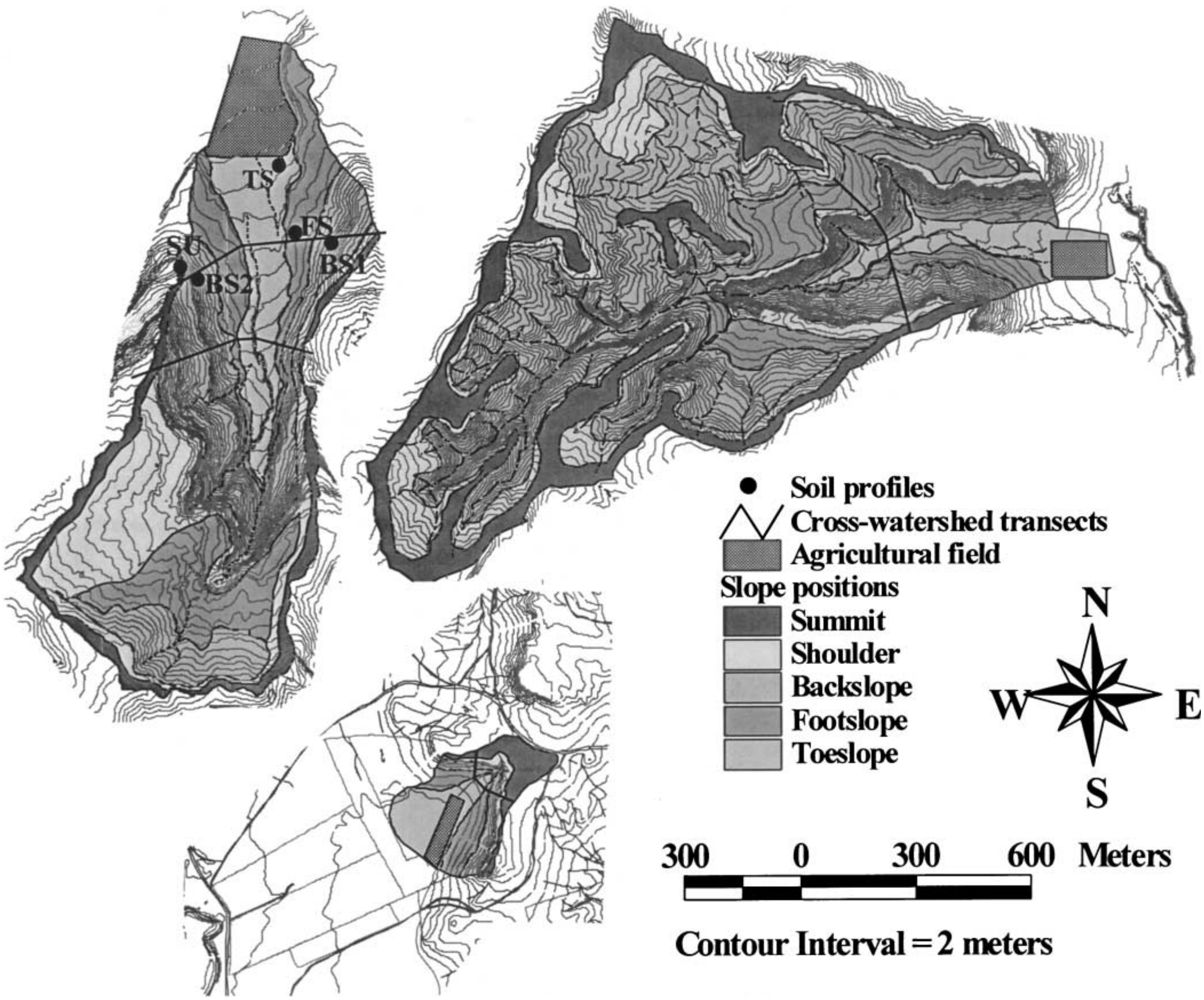

Fig. 3. Topography, slope positions, transect locations, and representative soil profile locations (see Table 1) within the Sanchez (upper left), Weekoty (upper right), and Laate watershed study sites on the Zuni Indian Reservation.

shallow A-2Cr horizon sequences on upper backslopes, gradually thickening to deep, well-developed A-Bt-2Cr Alfisols on footslopes. Soils on alluvial toeslopes feature well-developed Bt horizons that indicate long-term stability of the alluvium, overlain by stratified loamy sediments that generally lack soil structure and significant SOM accumulation. Backslopes are both the most extensive and steepest slope position at all three study watersheds (Fig. 3, Table 2). We noted evidence of dynamic erosion and deposition at each of the slope positions as rills, pedestaled plants and pebbles, and accumulations of slope wash materials, including sand, gravel, and organic material, behind downed logs and woody debris.

Vegetation patterns in the three watersheds are marked by distinct patchiness typical of pinyon-juniper woodlands and scrub-shrub grassland communities (Table 3). The patchiness creates high variability in cover plot data (standard deviations are generally higher than means) but consistent patterns emerge from composite analyses of the eight hillslopes. Herbaceous ground cover (grasses and forbs) and tree canopy cover (Table 3) follow opposite trends on the hillslopes. Tree cover is densest on backslopes where there is very little ground cover.

As with soils, plant species are divided into distinct associations by slope position (Table 3). Backslopes are characterized by pinyon, juniper, and Gambel oak growing singly or in clumps with thick litter layers beneath canopies and bare soil in interspaces. Summit and shoulder positions typically have the largest component of ponderosa pine (*Pinus ponderosa* P. Lawson & C. Lawson) along with pinyon and juniper, and some Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] in protected areas. Tree stands are more open on summits than on backslopes. The wider interspaces are often covered by grass [typically *Stipa* spp., blue grama {*Bouteloua gracilis* (Kunth) Lag. ex Griffiths, nom. illeg. [syn. *B. oligostachya* (Nutt.) Torr. ex A. Gray]}, bottlebrush squirrel tail [*Sitanion hystrix* (Nutt.) J.G. Sm. (= *Elymus elymoides* subsp. *elymoides*)], and mutton grass [*Poa fendleriana*

Table 1. Selected soil profile data from Sanchez study site.†

Horizon	Depth	Dominant color (moist)	Structure			Rock frags‡	Texture			Textural class	Boundary
			Grade	Size	Type		Sand	Silt	Clay		
	cm					%					
ProfileSU: Summit Position.§ Coarse loamy, mixed, mesic Aridic Lithic Ustorthents.											
Broad north sloping ridge; 4 percent slope; residual and eolian parent materials derived from sandstone caprock.											
A	0–12	7.5YR 4/4	Wk	Fi	Sbk	0	77	13	10	lfs	CS
Cr	12–35	7.5YR 5/4	Massive/vesicular			–	72	13	15	sl	CS
R	35+	7.5YR 5/6	Sandstone			–	–	–	–		
Profile BS1: Backslope Position. Loamy, mixed, mesic, shallow Aridic Ustorthents.											
West facing 27 percent slope; loamy colluvium over silty clay residuum from fine-grained sedimentary rocks.											
A–AC	0–21	10YR 5/5	Wk	Fi	Sbk	0	36	34	30	cl	CW
2Cr1	21–32	10YR 5/5	–	–	–	–	22	45	32	sicl	GS
2Cr2	32–41	10YR 5/6	–	–	–	–	27	43	31	sicl	GS
2Cr3	41–61	2.5Y 5/5	–	–	–	–	26	44	30	sicl	GS
2Cr4	61–78+	2.5YR 5/4–5/6	–	–	–	–	13	56	31	sicl	
Profile BS2: Backslope Position. Clayey-skeletal, mixed, mesic Aridic Haplustalfs.											
East facing 31 percent slope; loamy colluvium over silty clay residuum from fine-grained sedimentary rocks.											
A1	0–6	10YR 4/4	Wk	Med/fi	Sbk	20	25	37	38	cncl	CS
A2	6–25	10YR 4/5	Mod	Fi	Sbk	30	24	40	36	cncl	CS
Bt	25–42	10YR–2.5Y 5/4	Wk/mod	Med/fi	Sbk	50–60	22	36	42	vcnc	AS
Btk	42–63	10YR 5/4	Mod	Med/fi	Sbk	45–50	19	32	48	vcnc	DS
2Btk	63–83	10YR 6/3, 2.5Y 6/6-5/2	Wk/mod	Med/fi	Sbk/abk	35	23	37	41	vcnc	GS
2Crk	83–87+	2.5Y 5/2	–	–	–	–	8	47	45	sic	
Profile FS: Footslope Position. Fine, mixed, mesic Aridic Haplustalfs.											
West facing 7 percent slope; loamy colluvium over sedimentary rock residuum.											
A1	0–6	10YR 4/3	Mod	Med/fi	Pl	20	47	33	20	cnl	CS
A2	6–18	10YR 4/3	Wk	Med/fi	Sbk	15	45	28	27	cnl	AS
BAt	18–38	10YR 4/3	Wk	Med/fi	Pr	5–10	38	32	30	cl	GS
Bt	38–58	10YR 4/4	Wk	Med/fi	Pr	10	38	34	27	cl	CW
Btss	58–71	10YR 4/4–4/6	Str	Med/fi	Pr	10	39	22	39	cl	CS
Btkss	71–84	10YR 5/5	Str	Med/fi	Pr	5	32	28	40	c	GS
2Btk	84–100	10YR 5/4,5/6	Mod	Med/fi	Pr	5	18	45	37	sicl	CS
2BCtk	100–127	10YR 5/4,5/6–2.5Y 5/3	Mod	Fi	Sbk/abk	5	23	44	33	sicl	AS
3Cr1	127–162	5Y 3/1	Massive with slickensides			–	4	31	65	c	AS
3Cr2	162–165	5Y 4/1	Massive (fissile rock strct.)			–				c	AS
4R	165–170+	7.5YR 5/6–5/8,2.5Y 5/3	Sandstone								
Profile TS: Toeslope Position. Fine, mixed, mesic Aridic Haplustalfs.											
North facing 3 percent slope; loamy alluvium and colluvium over sandy strata.											
A	0–7	10YR 5/3	Wk	Fi	Sbk/gr	5	66	23	11	fsl	AS
BAt	7–18	10YR 4/3	Mod	Med/fi	Sbk/gr	2	37	34	29	cl	AS
Bt	18–47	10YR 4/3	Mod	Med/fi	Pr/abk	2	28	34	38	cl	AS
Btk1	47–65	10YR 4/3.5	Mod	Med/fi	Sbk	2	30	36	34	cl	AS
2Btk2	65–77	10YR 4/4	Mod/wk	Fi	Sbk	40–50	48	24	28	grscl	CS
2BC	77–116	10YR 4/4	Mod/wk	Fi	Sbk¶	25–35	58	21	21	grscl	AS
3C1	116–135	10YR 4/4	Massive¶			5	48	26	26	scl	AS
4C2††	135–155	10YR 4.5/4	Massive (stratified)			15	62	18	20	grscl	
5Ab††	134–155	10YR 3/2	Mod/wk	Fi	Sbk	0	22	42	36	cl	

† Abbreviations: A, abrupt; Abk, angular blocky; C, clear; c, clay; cl, clay loam; cnc, channery clay; cncl, channery clay loam; cnl, channery loam; Co, coarse; D, diffuse; Fi, fine; fsl, fine sandy laom; G, gradual; Gr, granular; grscl, gravelly sandy clay loam; lfs, loamy fine sand; Med, medium; Mod, moderate; Pl, platy; Pr, prismatic; S, smooth; Sbk, subangular blocky; scl, sandy clay loam; sic, silty clay; sicl, silty clay loam; sl, sandy loam; Str, strong; vcnc, very channery clay; W, wavy; Wk, weak.
‡ Rock fragment content inappropriate for paralithic horizons.
§ Compiled from descriptions at four transect points.
¶ Partly stratified.
†† Portion of this depth interval had buried A horizon with 8010 ±80yr radiocarbon age in soil organic matter. Profile augered from 155 to 300 cm consisted of gravelly sandy loam and sandy loam C horizons.

(Steud.) Vasey] shrubs {typically wavy-leaf oak (*Q. undulata* Torr.), mountain mahogany (*Cercocarpus montanus* Raf.), flowering ash (*Fraxinus cuspidata* Torr.), and antelope bitterbrush [*Purshia tridentata* (Pursh) DC.]}, and microbiotic crusts. Toeslopes are covered by big sagebrush (*Artemisia tridentata* Nutt.), western wheatgrass {*Agropyron smithii* Rydb. [= *Pascopyrum smithii* (Rydb.) A. Love]}, and blue grama with components of rabbitbrush [*Chrysothamnus nauseosus* (Pall.) Britton] and weedy herbaceous vegetation in wash areas.

Particle-size distribution follows distinct trends along the hillslope transects (Table 4) with finest soils derived from siltstone parent materials on backslopes and coarsest soils derived from sandstone parent materials on summits and loamy alluvium on toeslopes. This pattern is opposite of the broadly accepted hillslope models

Table 2. Areal extent of each slope position within each study watershed.

	Laate	Sanchez	Weekoty	Total
	Ha			
Summit	1.6	7.4	24.1	33.1
Shoulder	0.3	15.3	22.1	37.7
Backslope	1.1	18.1	55.6	74.8
Footslope	1.8	16.9	17.5	36.2
Toeslope	2.4	10.7	6.2	19.3
Total	7.3	68.4	125.4	201.1

Table 3. Estimated percent areal cover averaged across all sites by slope position. Data from all eight hillslopes.

Slope position	n	Grasses	Forbs	Shrubs	Oaks	Juniper	Pinyon	Ponderosa pine	Litter	Bare Soil	Microbiotic crusts
		%									
Summit	35	9a†	8a	17a	11ab	8ab	5ab	5a	32ab	35ab	2.9a
Shoulder	37	5a	6a	10a	3ac	3bc	14a	0b	22a	27ab	0.4b
Backslope	136	6ab	5a	18a	17b	9a	11a	2b	36a	26a	0.3b
Footslope	69	12c	16b	11a	1c	10a	9ab	0b	27b	30ab	2.0ab
Toeslope	47	20c	19b	36a	0c	0c	2b	0b	20a	33b	1.1ab

† Values followed by different letters within columns are significantly different at the $P = 0.05$ level.

presented by Ruhe and Walker (1968) that describe slopes with constant parent material.

Contents of total organic C, N, and P, as well as C:N ratios, of surface soil closely fit negative parabolic models with highest values on backslopes (Fig. 4). Plant-available N and P contents as proportions of total N and P, as well as pH, follow linear models with lowest values on summits and highest on toeslopes. Ammonium-N concentrations on the Sanchez hillslopes increase linearly through the backslope and footslope sections but remain relatively constant along the hillslope continuum as a whole. Nitrate-N content is highly variable and does not follow a distinct trend along the hillslopes. These models fit both the composite hillslope continuum (Fig. 4) and the composite mean values by slope position (Table 4). While we did not differentiate between total- and organic-P fractions, the strong correlation between total P and organic C ($P < 0.025$) suggests that changes in total-P concentration along the hillslopes likely result from SOM dynamics rather than rock weathering processes.

DISCUSSION

The horizontal stratigraphy of the Colorado Plateau combined with the high-elevation semiarid climate and intense convective summer thunderstorms, results in distinctive mesa-canyon topography with broad, level hilltops and steep, lithologically segmented hillslopes. This topography creates a unique landscape model with discrete landforms that have different but interconnected SOM processes. Fig. 2 is representative of our hillslope transects but the landscape as a whole is more complex, with the sequence of shoulder through footslope positions often repeating several times on mesa slopes (see Fig. 3). In general, the degree of soil development suggests dynamic erosion and deposition of surface horizon material over stable residuum and argillic subsurface horizons at each of the slope positions (Table 1). Similar distribution of clay content, vegetation, and SOM content among the five slope positions, with densest tree canopy and highest SOM content on the soils of backslopes, which have the highest clay contents, suggests that these parameters are controlled by underlying lithology (Table 3, 4, Fig. 4), and, more directly, its impacts on soil water holding capacity. The availability of N and P increases linearly and independently of slope position, however; even as total SOM content decreases (Fig. 4). This suggests that N and P availability are influenced by distance along the hillslope as well as plant community factors, possibly facilitated by mixing and physical disintegration as organic matter and sediments move downslope.

Table 4. Concentrations and ratios of soil properties averaged by slope position for all three study sites.

Slope position	n	Mean slope	Sand	Silt	Clay	Organic C	Total N	C:N	pH
		%				g kg^{-1}			
Summit	35	7	61a†	20a	19a	11a	1.1a	12ad	6.20a
Shoulder	37	14	66a	21a	13b	14ab	1a	14bc	6.47ab
Backslope	136	33	44b	30b	26c	19c	1.4b	15c	6.56b
Footslope	69	12	49bc	27c	24c	15b	1.2a	13ab	6.74c
Toeslope	47	5	54c	26c	20a	12ab	1.2a	10d	6.68bc

† Values followed by different letters within columns are significantly different at the $P = 0.05$ level.

Summit Positions

Surface soils on the broad, gently sloping summit positions in this study are relatively stable with respect to erosion and deposition, as indicated by well-established grasses and microbiotic crusts in canopy interspaces and weathered bedrock residuum parent materials (Table 1). Litter from the mixed ponderosa pine, pinyon, juniper, and oak forests covers >30% of the soil surface (Table 3), but soil nutrients (organic C, total N, and total P) are low compared with those of downslope positions that have even less herbaceous ground cover. This may suggest a lack of mixing from erosion and deposition on the relatively level summits. Low soil C:N ratios suggest in situ decomposition rather than removal and replacement with fresh litter. Low mineral N and P concentrations, as well as low available P:total P and NH_4^+–N:total N ratios suggest an immobilizing microbial environment typical of stable plant communities (Schimel, 1986). This type of stability, where disturbance (e.g., cultivation, fire, or dynamic erosion and deposition) is not a driving component, leads to well-established soil microbial communities that rapidly immobilize inorganic nutrients so SOM turnover rates may be relatively high but concentrations of inorganic nutrients are low (Stark and Hart, 1997).

Backslopes

Backslopes, with steeper gradients, slowly permeable subsoils, and lack of herbaceous understory vegetation, frequently generate runoff (Lagasse et al., 1990). The relatively large areal extent of backslopes suggests that the dynamic erosion and deposition are important factors in the landscape (Fig. 3, Table 2). Surface disturbance in the form of erosion and deposition (evident in numerous rills, pedestaled plants and pebbles, and accumulations of slopewash material) mixes, sorts, and transports soils and forest litter, possibly preventing establishment of an understory plant community. Rela-

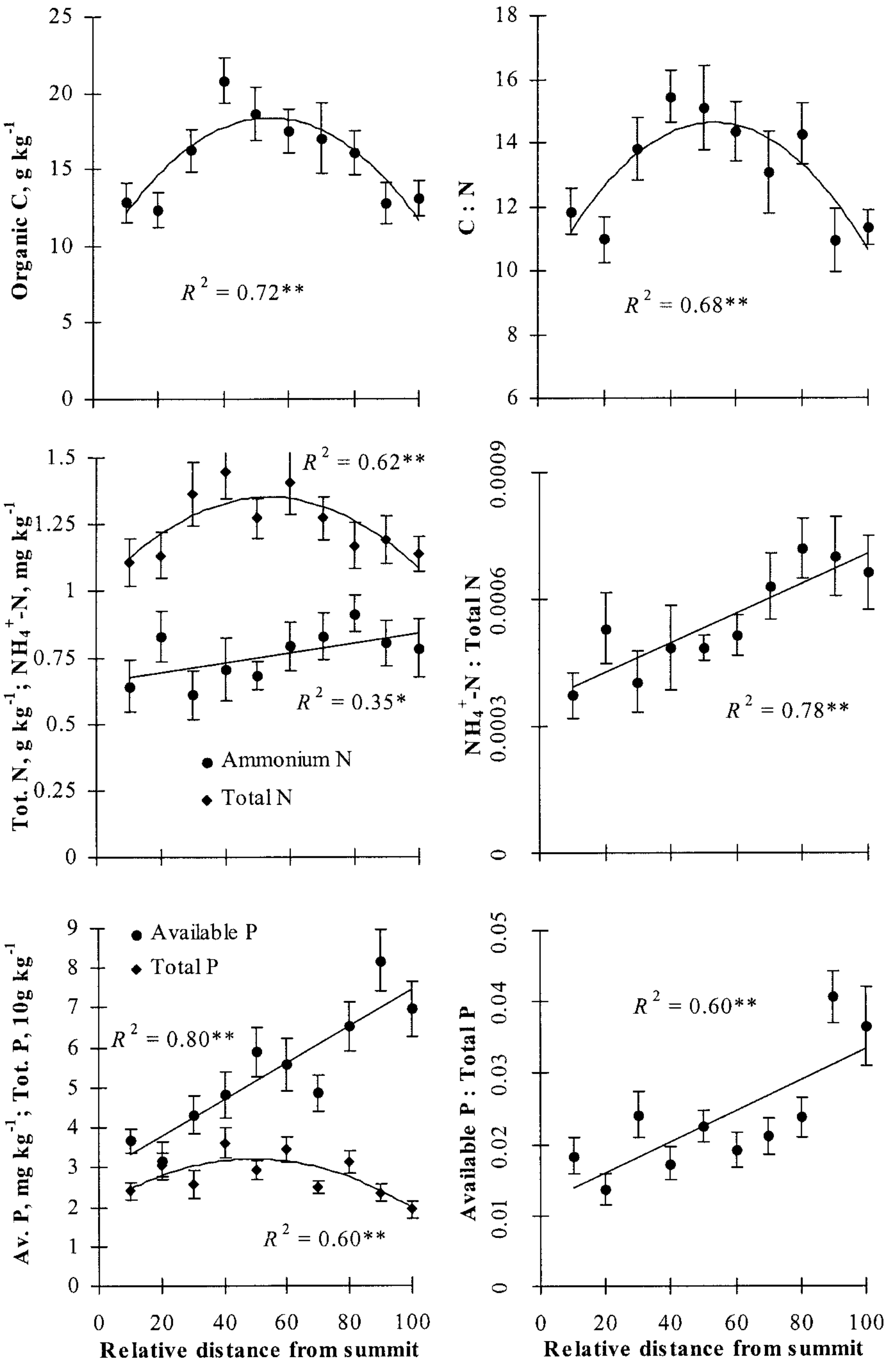

Fig. 4. Soil organic matter components along summit to toeslope composite hillslope continuum. Backslopes extend from ≈27 to 55 and toeslopes from 89 to 100 relative distance units along the *x*-axis. Each point is average of 10 units. Error bars represent standard error; *, significant at the 0.05 level; **, significant at the 0.005 level.

tively long slope lengths mean that these effects increase progressively downslope. Soil concentrations of organic C, total N, and total P are highest in the backslope positions, suggesting that slopewash processes mix forest litter with the loamy surface soils. Moving down the hillslope transects, C:N ratios increase markedly at the top of the backslopes where the density of pinyon, juniper, and oaks increases (Table 3). Then C:N ratios gradually decrease through the steep forested slopes. This suggests that organic materials are both moving downslope and decomposing. Rising NH_4^+–N and available P concentrations, along with increasing available P:total P and NH_4^+–N:total N ratios (Fig. 4), suggest a more mineralizing soil environment on backslopes than summit positions, which may also be a function of forest litter decomposing and being carried downslope. The clayey textures of the backslope soils may also contribute to a more mineralizing soil environment by enhancing soil moisture conditions, but the linear increases in mineral N and P concentrations through the foot- and toeslope positions, with progressively lower clay contents, may be better explained as progressive decomposition as material is moved downslope during frequent summer runoff events.

These trends may reflect increasing erosive power with increasing slope length. Rain splash and sheet flow on upper backslopes remove forest litter as it begins to decompose so that SOM is dominated by relatively fresh, high C:N ratio litter in an N-limited, immobilizing soil environment. Plant-available nutrients increase with decreasing elevation as summer runoff events mix partly decomposed material from upslope with fresh litter beneath the pinyon, juniper, and oak canopy, possibly stimulating mineralization. This is suggested by decreasing total concentrations of C, N, and P (overall loss of SOM) but increasing mineral N and P forms through lower backslope and footslope positions (Fig. 4). We observed fresh accumulations of mixed sediment and organic matter after precipitation events.

Footslopes and Alluvial Toeslopes

The soil C:N ratios continue to decrease as mineral N and P increase through footslope and toeslope positions (Fig. 4). Abundant herbaceous ground cover in lower slope positions may be a result of enhanced moisture and available-nutrient conditions. This could lead to a more stable surface soil environment and to microbial immobilization, but the influx of relatively highly mineralized slopewash material (colluvium), combined with occasional erosion and deposition, apparently outpaces and disrupts immobilization processes to maintain long-term productivity even where soils on alluvial valley floors have been farmed for many generations (Norton, 1996; Bull, 1997; Homburg, 2000). Schimel et al. (1985) noted the opposite in the less dynamic landscape (i.e., with denser ground cover, lower erosion rates, and gentler precipitation) of eastern Colorado's shortgrass prairie: decreased mineral N and higher C:N ratios on lower slopes. They attributed this to greater biomass production due to enhanced soil moisture, which caused microbial immobilization to outpace mineralization rates.

Classical catena studies show that quantity and quality of SOM, as well as soil texture, pH, and other properties change systematically down hillslopes (Conacher and Dalrymple, 1977; Jenny, 1980; Gerrard, 1992). Many studies document changes in soil properties with slope position, and define processes associated with sediment movement, sorting, and accumulation as it pertains to soil morphology (Ruhe and Walker, 1968; Kleiss, 1970; Honeycutt et al., 1990). Each of these studies defines increasing SOM concentrations with distance from summit along trends that mirror fine soil fractions. Aguilar and Heil (1988) noted increasing C, N, and P concentrations, as well as narrowing C:N ratios, with decreasing elevation on North Dakota rangeland hillslopes. They suggest accumulation of runoff-transported SOM on lower slopes and infer progressive downslope increases in inorganic N concentrations. Our results generally show opposite trends in both particle-size distribution and concentrations of SOM constituents from these models of hillslope processes. We attribute these differences to the distinct mesa-canyon topography that controls vegetation patterns of the Colorado Plateau landscape. Summit position soils form in sandy parent materials derived from the sandstone caprocks; backslope and footslope soils form in residuum and colluvium of the weathered, slope-forming shales; and toeslopes, which in this hillslope system double as alluvial fans or terraces, form in loamy colluvium and alluvium transported from adjacent hillslopes and deposited over sandy strata from the larger fluvial system (see Fig. 3, Table 1).

Studies of the effects of vegetation on SOM content and composition show that different species can have distinct impacts (Klemmedson, 1991; Klemmedson and Wienhold, 1991). Klemmedson (1991), for instance, found that Gambel oak had significant positive impacts on soil fertility in Arizona ponderosa pine stands; much more than actinomycetes-associated N-fixing shrubs such as mountain mahogany. The predominance of Gambel oak, pinyon, and juniper trees on the steep backslopes of our study areas may partly explain the peak in SOM contents on this slope position.

Similar parabolic trends followed by total organic C, N, and P content, clay content, and tree cover suggest that changes in SOM content are partly associated with particle-size distribution and/or vegetation. Each of these important factors in the soil microbial environment increases from summits to backslopes, possibly from enhanced moisture content with finer soil texture, and then decreases through footslopes and toeslopes as surface soil texture becomes sandier. Carbon:N ratios, however, are high on backslopes and lower on foot- and toeslopes, which is opposite what may be expected if soil texture and associated moisture holding capacity enhanced mineralization. Like SOM and clay content, NH_4^+–N and available P concentrations in surface soils (especially relative to total N and P concentrations) also increase from summits to backslopes but then continue to increase independently of other soil, vegetation, and SOM parameters (Fig. 4). This suggests that mineralization increases as a function of distance through the hillslope system independently of the soil environment (e.g., SOM content and soil texture). We believe that increasing mineralization reflected in decreasing C:N ratios and increasing N and P availability results largely from physical breakdown and translocation of organic materials with frequent summer runoff events that alternate with hot dry conditions.

Most studies of SOM distribution in Southwestern pinyon-juniper woodlands and scrub-shrub grasslands focus on tree and shrub encroachment that increases soil heterogeneity, creating vegetated patches with depleted interspaces (Allen, 1991; Schlesinger et al., 1996). Development of these resource islands is both cause and effect of changing runoff and erosion regimes in a positive feedback relationship (Abrahams et al., 1995). Recent work has focused on effects of vegetation patches on runoff and erosion yields (Wilcox, 1994), redistribution of sediments among pinyon-juniper patches and intercanopy zones (Reid et al., 1999), and effects of shrub-patch-induced accelerated erosion on nutrient losses (Schlesinger et al., 1999). The backslopes of our study sites, with nearly mutually exclusive woody canopy and herbaceous ground cover, appear to be most affected by the resource island effect, which probably contributes to increased runoff, which transports and facilitates decomposition of forest litter.

CONCLUSIONS

The results of this research provide a basis for understanding watershed hillslope characteristics that contribute to sustained productivity of semiarid alluvium- and colluvium-derived soils of Colorado Plateau-type landscapes. Relationships between soil, landform, and vegetation patterns point to the forested backslopes as a driving force behind movement and processing of runoff, sediment, and organic materials. The relatively large areal extent, steepness, slowly permeable subsoils, and combination of bare soil and tree species that produce large amounts of forest litter on backslopes contribute to favorable hydrological properties and fertility of traditional agricultural fields on soils derived from alluvium.

Traditional alluvial fan farming remains an important cultural activity among the Zuni and other Southwestern Native American Tribes, but the importance of hydrological connectivity between upland hillslopes and alluvial landforms extends beyond its value to traditional agriculture. Sediments, organic materials, and runoff from hillslopes are valuable resources for sustaining ecological diversity and productivity in flood plains, riparian areas, alluvial fans, and downstream aquatic systems. When such products of hillslope processes are deposited on functional flood plains and alluvial fans they store sediments, attenuate peak flows, and absorb runoff, which can maintain down stream perennial flows. Loss of functional hydrological connectivity (due to channel incision or channelization) means that products of hillslope erosion are lost to alluvial landforms and become environmental liabilities in a feedback spiral of soil degradation where sediments and constricted flows damage downstream aquatic systems. Channel incision, or arroyo cutting, is an important driver of environmental degradation across the southwestern USA and other arid and semiarid regions of the world (Cooke and Reeves, 1976; Elliot et al., 1999).

This research improves understanding of one component of the connection between upland slopes and alluvium-derived soils on the Zuni Indian Reservation and describes a hillslope model that applies to lithologically segmented landscapes such as the Colorado Plateau. The fluvial system that delivers hillslope materials to alluvial fans, as well as nutrient dynamics and agricultural use and conservation within alluvial fans are other important components warranting further study. Understanding these aspects of key landform processes could contribute to more effective conservation, protection, and restoration of degraded semiarid landscapes.

ACKNOWLEDGMENTS

This work was funded by National Science Foundation grant no. DEB-9528458. We are indebted to the Zuni Sustainable Agriculture Project, the Zuni Conservation Project, and the Zuni Tribe. We thank Jeff Homburg, Todd Carlson, Marnie Criley, and Clara Wheeler for laboratory analysis and Troy Lucio, Lindsay Quam, Vanissa Laahty, and participants in Zuni's Job Training Partnerships Act (JTPA) program for field assistance. We are grateful to Tom DeLuca, Urszula Choromanska, Stephen Siebert, and two anonymous reviewers for technical advice and editorial review. Manuscript preparation was supported by the Utah Agriculture Experimental Station.

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